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CALCULATION PRINCIPLES FOR A SYNCHRONOUS ELECTROMAGNETIC CLUTCH

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16. Abstract A detailed explanation of the calculation principles for a synchronous salient-pole electromagnetic clutch with lumped excitation windings supplied by direct current. Practical recommendations are given.			
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CALCULATION PRINCIPLES FOR A SYNCHRONOUS ELECTROMAGNETIC CLUTCH

M. A. Panasenkov

A synchronous electromagnetic clutch with lumped excitation wind- /39*
ing located on the poles and supplied by direct current, possesses a
number of advantages, in contrast to a synchronous reactive clutch (re-
active motor) with distributed alternating current windings. It is
simpler in structure and has a large angular momentum.

A sketch of one type of synchronous clutch used for vacuum equip-
ment [1] drives is shown in Figure 1. The driving part of the clutch
1, like the stator of a d.c. machine, is coupled to a d.c. shunt motor
used to drive the vacuum equipment at a given speed of rotation. The
driven part of the clutch 2 is itself a massive salient-pole steel ro-
tor. The driving and driven part of the clutch are separated by a non-
conducting cylinder 3, which is attached with flange 4 to the vacuum
equipment housing. Clutches such as these are successfully used at the
present time on a number of devices.

THE CLUTCH OPERATIONAL PRINCIPLE is analogous to the principle of
a synchronous reactive motor. However, the latter operates at a con-
stant input voltage and, consequently, with a practically-constant mag-
netic flux, whereas the synchronous electromagnetic clutch operates at
a constant excitation magnetizing force F_B and a changing magnetic flux.

ELECTROMAGNETIC SYNCHRONOUS MOMENT. As is known, the difference
in permeance along d , lengthwise to the axis of the rotor and q perpen-

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pendicular to the axis of the rotor causes a synchronous moment M_c which in synchronous reactive motors is called the reactive moment.

The least reluctance to the magnetic flux is during idle running of the clutch when the axis d of the rotor coincides with the axis of the poles. Under load, the lengthwise axis of the rotor tilts from the axis of the poles to the side of the lagging rotor (Figure 2). The magnetic field is deformed and the reluctance grows as a result of the increase of the air gap between the rotor and the poles. The magnetic flux then diminishes. This reduction is accompanied by a reduction of the saturation, reluctance and magnetic potential in the steel. As a result, the magnetic potential is redistributed over the separate parts of the magnetic circuit.

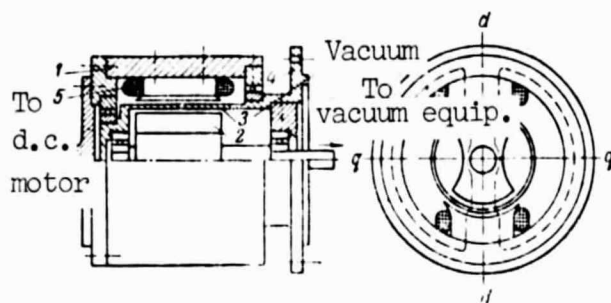


Figure 1: Sketch of a synchronous electromagnetic clutch for vacuum equipment drives.

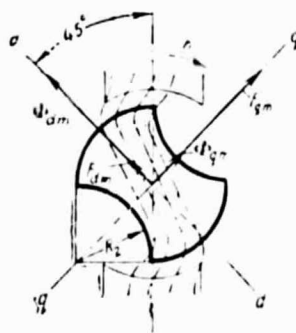


Figure 2: Deviations of design formulas. ϕ_{dm} , ϕ_{qm} , and F_{dm} , F_{qm} are the complex amplitude of the flux and magnetic potential of the rotor along its longitudinal and transverse axes, located in a complex plane; n is the speed of rotation of the poles.

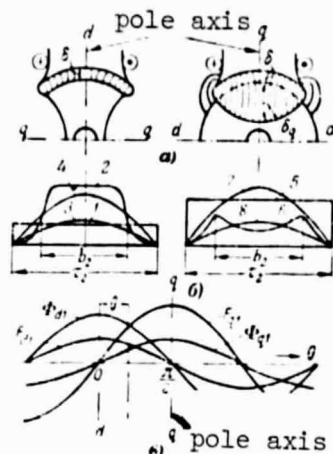


Figure 3: Approximate Distribution of the magnetic field in the air gap of the clutch.

1, 2 are the curves of magnetic potential and magnetic induction. 3 and 4 are the first harmonic of magnetic potential and induction along the longitudinal axis of the rotor. 5, 6, 7, and 8 are the same as 1, 2, 3, and 4 except along the transverse axis of the rotor. Φ_{dl} , F_{dl} , Φ_{ql} and F_{ql} are the first harmonics of flux and magnetic potential along the longitudinal and transverse axes of the rotor. τ_2 is the pole division of the rotor, b_2 is the arc of a protrusion or recess in the rotor.

The minimum magnetic flux is obtained at the position of the rotor where its axis q coincides with the axis of the poles (Figure 3a). With the reduction of flux, the potential force applied across the common air gap δ between the poles and the circumference of the rotor is reduced as well. If the common gap δ which occurs during coincidence of axis d with the axis of the poles (Figure 3a) is subtracted from the air gap along the q axis when it coincides with the axis of the poles, then we obtain a varying gap that depends on the recess of the rotor along the q axis. The gap causes both a change of magnetic flux and a redistribution of magnetic potential as the position of the rotor changes relative to the axis of the poles.

Approximate variations of the redistribution of the magnetizing

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force equivalent to the magnetic potential*, and the induction on pole division τ_2 along the longitudinal and transverse axes of the rotor are shown in Figure 3b, 3c. At a certain load, when the rotor turns by an angle θ relative to the axis of the poles, the projections of the fluxes and magnetizing force on the pole axis will be given by the following equations:

$$\Phi_{d1} = \Phi_{dm} \cos \theta; \quad (1)$$

$$F_{d1} = F_{dm} \cos \theta; \quad (2)$$

$$\Phi_{q1} = \Phi_{qm} \sin \theta; \quad (3)$$

$$F_{q1} = F_{qm} \sin \theta, \quad (4)$$

where Φ_{dm} , F_{dm} , Φ_{qm} , and F_{qm} are the amplitudes of the first harmonics.

The transverse magnetizing force F_{q1} lags behind the longitudinal flux Φ_{d1} by an angle $\pi/2$. Consequently, the torque, which is determined by the magnetizing force over the pair of poles, by the product $1/2 \Phi_{d1} F_{q1}$, is a driving force. It influences the rotation of the flux. The longitudinal magnetizing force F_{d1} leads the transverse flux Φ_{q1} by the angle $\pi/2$. Therefore, the torque due to their interaction has a braking effect against the torque of the flux.

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If the clutch has p pairs poles, then the resulting synchronous moment is given by:

$$M_c = \frac{p^2}{2} (\Phi_{d1} F_{q1} - \Phi_{q1} F_{d1}), \quad (5)$$

or, in agreement with equations (1) and (4),

$$M_c = \frac{p^2}{4} (\Phi_{dm} F_{qm} - \Phi_{qm} F_{dm}) \sin 2\theta. \quad (6)$$

Calculations of the build-up of fields and the separation of harmonics, are rather complicated. Therefore, we will present simplified

*Potential force, equivalent to the magnetizing force, means the potential force equal to the magnetizing force of the rotor along the d axis and the potential force equal to the magnetizing force over the section $2\delta_3$ along the q axis.

calculations.

FORMULAS FOR PRACTICAL CALCULATIONS. Formulas (5) and (6) can be derived even for the case where equivalent sinusoids are used instead of the first harmonics. It is easy to shift from the equivalent sinusoids to the actual magnetic fluxes and magnetic potentials. Formula (6) can be presented in the following form:

$$M_c = \frac{p^2}{2\sqrt{2}} (\Phi_{dm} F_q - \Phi_{qm} F_d) \sin 2\theta. \quad (7)$$

Here,

$$\left. \begin{aligned} \Phi_{dm} &= B_{\delta d} l_d b_d; \quad \Phi_{qm} = B_{\delta q} l_q b_q; \\ F_d &= H_d l; \quad F_q = 2\delta_{cq} H_{\delta q}; \end{aligned} \right\} \quad (8)$$

where Φ_{dm} , Φ_{qm} , $B_{\delta d}$, $B_{\delta q}$ are the maximum flux and average induction in the air gap along the longitudinal and transverse axes of the rotor,

F_d and F_q are the real magnetic potentials of the rotor along the longitudinal and transverse axes on a pair of poles.

d , $2\delta_{cq}$ is the average length of the magnetic path of the rotor along the longitudinal and transverse axes.

l_d , b_d , l_q , and b_q are the calculation lengths of the curve of the pole along the longitudinal and transverse axes of the rotor.

THE CHOICE OF CLUTCH PARAMETERS should be made starting with the condition of the greatest maximum moment M_{cm} obtained from (7) at $\theta = \pi/4$, and a sufficient starting asynchronous moment M_n . The magnitude of the pole arc of the rotor b_2 has a distinct influence on moments M_{cm} and M_n . Investigations shows that if the curve b_2 is taken equal to half the pole length of the rotor τ_2 , then the maximum moment M_{cm} obtained is relatively large with a sufficient magnitude of starting moment M_n . It is expedient to make the recess arc in the rotor of the two-pole clutch equal to the arc b_2 traversed by the radius of the rotor R_2 from the top of an equal sided tetragon circumscribed by

the circumference of the rotor (Figure 2). In this case, the average length of the air gap δ_{cq} is determined by the ratio of twice the area limited by the arc b_2 and its chord, to this chord.

$$\delta_{cq} = \frac{\pi - 2}{4\sqrt{2}} D_2 \approx 0.2D_2, \quad (9)$$

where D_2 is the diameter of the rotor.

The thickness of the rotor in the narrowest place, that is, along the q axis,

$$h_q = \frac{4(\sqrt{2} - 1)}{\pi} b_2 \approx 0.527b_2. \quad (10)$$

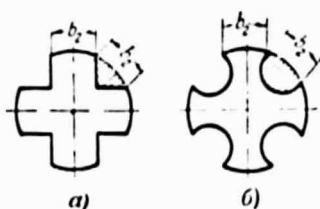
Calculations of the magnitude of b_d and l_d , along the length of which the induction B_{ld} is taken to be uniformly distributed, can be approximately determined from the known correlations

$$\left. \begin{aligned} b_d &= b_1 + 2\delta = b_2, \\ l_d &= l_1 + 2\delta. \end{aligned} \right\} \quad (11)$$

Analogously,

$$\left. \begin{aligned} b_q &= b_1 + 2\delta = b_2, \\ l_q &= l_1 + 2(\delta_{cq} + \delta). \end{aligned} \right\} \quad (12)$$

where b_1 and l_1 are the arc and length of the pole of the leading part of the clutch.



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Figure 4: Types of quadrupolar rotor designs.

It is usually convenient to fix the induction $B_{\delta d}$ during the calculations. Its value can reach 1.6 Tl and higher. The induction of the rotor in the narrowest section increases 1.9 times in agreement with equation (10). This causes an increase in F_d and reduces the synchronous moment in agreement with equation (7). In order that the induction in the narrowest section of the rotor be kept equal to $B_{\delta d}$.

the length of the rotor l_2 should be taken to be equal to $1.9 l_d$ according to (10). In this case the rotor receives approximately equal magnetic permeance along the longitudinal axis. The average length of the magnetic path d , considering the distortion of the magnetic lines in the axial direction can be taken as approximately equal to the diameter of the rotor D_2 . Increasing the length of the rotor leads to a reduction of F_d and an increase in the synchronous moment.

The air gap δ is given by the thickness of the wall of the vacuum cylinder 3 in Figure 1. As δ is increased, the potential force F_B increases; this in turn leads to an increase in M_c . In order that we may explain the influence of δ on M_c , we will make the assumption that the magnetic circuit of the clutch is not saturated. Disregarding the magnetizing force of the steel sections, we will have:

$$F_B = 2\delta H_{\delta d} = 2(\delta_{cq} + \delta) H_{\delta q}, \quad (13)$$

where $H_{\delta d}$ is given the value of the induction $B_{\delta d}$. In agreement with (13), we find

$$F_q = 2\delta_{cq} H_{\delta q} = H_{\delta d} \frac{\delta_{cq} \delta}{\delta_{cq} + \delta}. \quad (14)$$

From (14) it is obvious that as δ increases, F_q increases, and as a result, in agreement with (7), M_c increases.

However, under real conditions to disregard the magnetic potential of the steel along the longitudinal axis of the clutch is not permissible. On the contrary, it is satisfactory to take in the poles and depression of the leading part of the clutch as approximately 2 Tl. The saturated magnetic circuit of the leading part of the clutch, together with the common gap δ is itself a form of "magnetic accumulator" from which stored magnetic energy is released when the angle θ increases from 0 to 45 degrees. This increases the synchronous moment. The larger the saturation of the steel of the magnetic circuit (except the rotor), the larger will be the magnetic energy along the longitudinal axis of the clutch - that is, for $\theta = 0$. The synchronous moment will be larger with the same size of the synchronous electromagnetic clutch.

The strength of the magnetic field in the air gap along the transverse axis of the clutch, for coincidence of the axis of the rotor q with the axis of the poles, is determined by the equation

$$H_{\delta q} = \frac{F_n}{2(\delta_{eq} + \delta)k_q}, \quad (15)$$

where k_q is the coefficient which takes into account the magnetic potential in the poles and yoke of the leading part of the clutch along the transverse axis. Since the reluctance of the air gap along the transverse axis is great and the flux $\Phi_{\delta q}$ is small, the steel section of the magnetic circuit along the transverse axis will not be saturated and the coefficient $k_q \approx 1.02$ to 1.05 . Knowing $H_{\delta q}$, it is easy to find the induction $B_{\delta q} = \mu_0 H_{\delta q}$.

In the case of the quadrapolar clutch the average air gap of the rotor at $b_2 = r_2/2$ (Figure 4) is determined by the relationship of the cross-hatched area to the length of the chord equal to the side of an even-sided octagon, inscribed in the circumference. For the rotor presented in Figure 4a, we have

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$$\delta_{eq} = \left(\frac{1}{4} \sin \frac{\pi}{8} + \frac{\pi - 2\sqrt{2}}{32 \sin \frac{\pi}{8}} \right) D_2 \approx 0.121 D_2, \quad (16)$$

in Figure 4b,

$$\delta_{eq} = \left(\frac{\pi}{8} \sin \frac{\pi}{8} + \frac{\pi - 2\sqrt{2}}{32 \sin \frac{\pi}{8}} \right) D_2 \approx 0.176 D_2. \quad (17)$$

In the latter case, the semicircle of the rotor recess is drawn from the middle of the chord with a radius equal to half of the chord. It follows that the length of the rotor l_2 should be equal to approximately $1.5 l_d$. Generally for a reduction of the magnetic potential F_d , the length of the rotor can be taken equal to the axial dimension of the excitation coil. In this case, the product $\Phi_{qm} F_d$ can be disregarded and equation (7) is significantly simplified.

$$M_c = \frac{P^2}{2\sqrt{2}} \Phi_{dm} F_q \sin 2\theta. \quad (18)$$

Keeping in mind the equation $b = b_2 = \tau_2/2$, from (18), at $\theta = \pi/4$ we find the equation for determining the basic dimensions of the clutch:

$$D_2 l_d \delta_{cq} = \frac{4 \sqrt{2}}{\pi p} \frac{M_{cm}}{B_{ld} H_{lq}}. \quad (19)$$

When $B_{\delta d} \approx (1.5 \text{ to } 1.7) \cdot 10^{-4} \text{ wb/cm}^2$, the quantity $H_{\delta q}$ can be roughly determined in relationship to the air gap from the empirical formula:

$$H_{lq} = 5000 \delta, \text{ a/cm}. \quad (20)$$

When the induction in the poles and yoke of the leading part of the clutch is equal to 2 Tl, formula (20) gives good results for rotor diameters in the range from 2 to 20 cm and higher.

CALCULATION PLAN. We will examine a specific example. Let it be assumed that $M_{cm} = 300 \text{ nm}$ and the thickness of the wall of this vacuum cylinder is equal to 3 mm. Taking $\delta = 0.4 \text{ cm}$, we find from (20) that $H_{\delta q} = 2000 \text{ a/cm}$. The technical conditions ordinarily limit D_2 or l_d . We will assume that the limiting value is $D_2 = 20 \text{ cm}$; then the induction is given from (19) as $B_{\delta d} = 1.6 \times 10^{-4} \text{ wb/cm}^2$ at $p = 1$ in agreement with (9) we find $l_d = 21 \text{ cm}$ and according to (11), $l_1 = 20.2 \text{ cm}$. From (8) for $b_d = b_2 = 15.7 \text{ cm}$, we find $\phi_{dm} = 0.528 \text{ wb}$.

Taking the induction in the pole and yoke of the leading part of the clutch equal to 2 Tl, we find the cross-section of the pole and yoke. The height of the pole is chosen, starting from the requirements of the distribution in the interpolar space of the necessary number of windings of the excitation coil. Using methods from the theory of machines, the magnetic potential is determined further on the separate parts of the magnetic circuit with consideration for the scatter along the longitudinal axis of the clutch. The magnetizing force applied along 2δ is equal to 10,200 a, but in the poles and yoke for steel of the type St. 2 for $B = 2$, Tl is equal to 9,200 a. For $l_2 = 1.9 l_d$, the induction in the rotor can be taken equal to $B_{\delta d}$. This induction for St.2 corresponds to $H_d = 14 \text{ a/cm}$. According to (8), for $d = D_2$ we find $F_d = 280 \text{ a}$. Then the potential force is $F_B = 19,680 \text{ a}$.

Having found from (9) that $\delta_{cq} = 4 \text{ cm}$, from (15), taking $k_q = 1.03$,

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we find $H_{\delta q} = 2170$ a/cm and from (8), $F_q = 17,300$ a, and the induction $B_{\delta q} = 0.273$ Tl. From (8) in agreement with (12) we have $\Phi_{qm} = 0.0127$ wb. From (7), for $\theta = 45^\circ$ and $p = 1$, we find $M_{cm} = 320$ nm which exceeds the given moment by 6.5%.

PRACTICAL RECOMMENDATIONS. 1. For a flux $\Phi_{qm} = 0.0127$ wb, the induction of the poles and yoke even for a 50% scatter of Φ_{qm} is equal to 0.72 Tl. The magnetic potential in the poles and yoke is approximately 2.7% of F_B . Thus the flux scatter along the transverse axis hardly influences F_q and, consequently, M_c .

2. The product $\Phi_{qm} F_d$ makes up an even smaller percentage of $\Phi_{dm} F_q$; therefore, the synchronous moment can be calculated from the approximate formula (18).

3. The magnetic potential in the poles and yoke along the longitudinal axis of the clutch are made up approximately of 50% of F_B . This increases the moment in comparison with the moment in the unsaturated clutch by almost two times along the longitudinal axis. This distinguishes the synchronous electromagnetic clutch from the synchronous reactive clutch, which can be used for the synchronous reactive motor. In the latter, the increase of saturation in the steel stator leads to increased loss and to excessive heating so that operation of the machine becomes impossible.

The induction of the air gap of the synchronous electromagnetic clutch $B_{\delta d}$ can reach 1.7 Tl and higher. Therefore, the synchronous moment can be 4 to 5 times more than in the synchronous reactive clutch for one and the same size.

4. Calculations show that the quadrapolar clutch for the same diameter of the rotor and the same induction along the longitudinal axis of the clutch gives a moment approximately 25% greater for the rotor shown in Figure 4a. The moment is 50% higher with the rotor shown in Figure 4b. The axial length of the clutch then diminishes.

5. For a given value of $B_{\delta d}$, the accuracy of the calculations

according to (18) depends only upon the accuracy of defining b_d , l_d , and F_q .

6. An increase in the synchronous moment when the basic size of the clutch is limited can be achieved by the use of a rotor with a permanent magnet.

7. For the same moment M_c , the unsaturated magnetic circuit of the clutch is heavier and more expensive than with the saturated one.

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